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A solar/gas fired absorption system for cooling and heating in a commercial building

HaiQuan Sun[a], ZhenYuan Xu[b], HongBing Wang[a], RuZhu Wang[b]*

[a]*Shandong Normal University – Lishan College, Shandong 262500, China*
[b]*Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China*

Abstract

Absorption cooling technologies have been researched for many years. The gas fired absorption chiller is stable and high-efficient but has high gas consumption. The solar hot water driven absorption chiller is clean and energy saving but hard to work steady and continuously. In this paper, a system for cooling and heating based on an absorption chiller that can be driven by both gas firing and solar hot water was proposed and built. The system is a hybrid capable of solar cooling in single effect and gas fired cooling in double effect and also thus a combination. It has the advantages of both solar driven and gas fired absorption systems. This system works in solar driven mode (single effect) when the solar energy is enough. It works in gas fired mode (double effect) when solar energy is not enough or solar hot water temperature is low. The design and operation strategy is to use solar at first and gas fired as a backup, thus fossil energy saving is obvious. Year round operation of the system was recorded and analyzed in a commercial 5 star hotel. Compared with the gas fired absorption system, the gas/solar driven absorption system can save 49.7% of the gas consumption.

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Keywords: Solar cooling, Solar heating, Absorption system, Gas fired, Hybrid energy system

1. Introduction

Absorption chiller is able to produce cold from different heat resources, for example, the solar hot water, industrial waste heat, gas firing heat and son on. Absorption cooling is one of the most important research areas of

* Corresponding author. Tel.: +86 21 62933838; fax: +86 21 62933250.
E-mail address: rzwang@sjtu.edu.cn

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refrigeration [1]. Among the different forms of absorption chillers, direct gas fired absorption chiller (double effect or even triple effect) is stable and has high cooling efficiency. This kind of chiller can also produce hot water in winter. But the energy consumption of the chiller is too high because its year round operations are all depend on fossil fuels like natural gases. This makes the operational costs and emission of CO2 high. Considering the clean and renewable properties of solar energy, solar thermal heat has been researched and developed by many researchers. Solar driven absorption cooling has been a hot topic for decades. It is more environmentally friendly than the gas fired absorption cooling. In recent years, both simulation and experimental works on different couplings of solar collectors and absorption chillers were carried out [2-4].

In simulation aspects, many researches about single effect LiBr-water absorption chiller were carried out [5-7]. F. Assilzadeh simulated and optimized a LiBr-water absorption chiller activated by evacuated tube solar collector working in Malaysia based on TRNSYS program [8]. Daily performance, long-term performance in a year and economic analysis were studied. M. Mazloumi studied a single effect absorption LiBr-water chiller driven by parabolic trough collector in Iran numerically [9]. The one-day performances from June to September were given. J.V.C. Vargas studied a heat and cooling cogeneration solar absorption system numerically [10]. A model including fundamental and empirical correlations was proposed for design and global optimization of the system. Besides, couplings of solar collector and other absorption chillers were also studied. M.J. Tierney simulated several solar absorption cooling systems including the single effect-plate system, the single effect-trough system, the double effect-plate system and the double effect-trough system [11]. Break-even points of solar fraction, cooling demand and other parameters were calculated. Linear Fresnel reflector concentrator direct driven ammonia-water generator-absorber-exchange absorption cooling system was proposed [12]. The mathematical model of this system considering the geometry, optics and other detailed parameters was built and studied. A solar cooling system that could work in solar driven single effect cooling and gas driven double effect cooling was proposed and simulated by the research group of Shanghai Jiao Tong University [13]. Economic analysis was also carried out. The system configuration of this system was similar to the system referred in this paper.

In experimental aspects, systems based on single effect chiller were also researched frequently [14-16]. A. Syed tested a flat-plate collector driven 35 kW single effect LiBr-water absorption chiller in Madrid [17]. The maximum instantaneous COP, daily average COP and period average COP were 0.60, 0.42 and 0.34 respectively. R. Lizarte studied a vacuum flat-plate collector driven 4.5 kW air-cooled single effect LiBr–water absorption chiller experimentally [18]. The experiment was carried out in Madrid. Results showed the mean COP and solar COP were 0.53 and 0.06 respectively. R. Lizarte also compared the operation of an indirectly air-cooled absorption chiller and a directly air-cooled absorption chiller [19]. The direct air-cooled system obtained higher thermal COP and electrical COP. A. Pongtornkulpanich tested a 10-ton single effect LiBr-water absorption chiller powered by evacuated tube solar collector in Thailand [20]. Solar collector delivered 81% of the thermal energy for the chiller. Pablo Bermejo built and tested a solar/gas driven double effect LiBr-water absorption system in Spain [21]. The system could be driven by direct-fired natural gas burner or pressurized hot water delivered from a linear concentrating Fresnel collector. The average and maximum daily efficiencies of the solar collector were 0.35 and 0.4 respectively. The daily average COP of the chiller was 1.1-1.25.

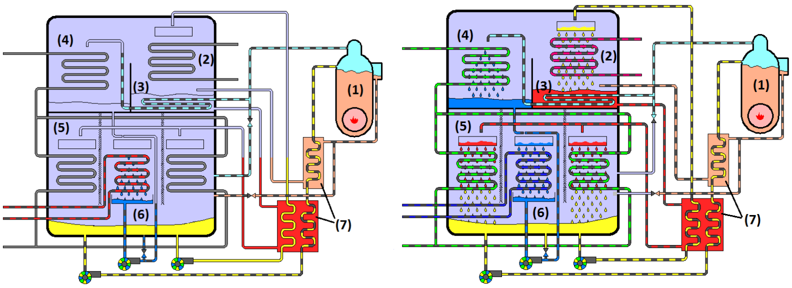
Although the solar driven absorption cooling technology has been developed very well, there still exist some problems to be solved. The solar power depends largely on weather and it cannot work at night. This makes the steady and continuous operations of solar driven absorption cooling very hard. Considering the low temperature solar collector driven single effect absorption cooling and the gas fired double effect absorption cooling have complementary advantages, a system combined of the two referred systems were built for commercial hotel cooling, heating and hot water supply. The system was composed of solar collectors, hybrid solar/gas driven absorption chiller and other components. It could work in both the gas fired double effect mode and the solar driven single effect mode, the hybrid working mode with solar and gas firing are also possible for which gas firing is considered as a backup for the control strategy. The year round operations of the system for cooling and heating were recorded and analyzed.

2. Hybrid solar/gas fired absorption chiller and its operation modes

The absorption chiller discussed in this paper was a hybrid solar/gas fired absorption chiller which can work in hybrid single/double effect refrigeration modes and heating modes. The photo and circulation diagram are shown in Figure. 1.

As is shown in the figure, the absorption chiller had three pressure level and 6 major components, i.e. the high pressure generator (1), the two low pressure generators (2)(3), the condenser (4), the left and right absorbers (5), the evaporator (6) and the solution heat exchanger (7). The absorption chiller had an extra low pressure generator comparing with conventional double effect absorption chiller. This extra generator worked for solar cooling, while the evaporator and absorbers were common. In this case, the solar powered single effect refrigeration and gas fired double effect refrigeration could work both independently or simultaneously. Among the different working modes, the solar powered single effect refrigeration mode had the highest priority. When solar power temperature was not high enough or the solar cooling couldn't afford the cooling consumption, the gas fired double effect refrigeration was activated.

(a)



(b) (c)

Fig. 1. (a) Hybrid solar/gas fired absorption chiller; (b) Circulation diagram for cooling; (c) Circulation diagram for heating.

1-gas boiler (high pressure generator), 2-low pressure generator for single effect circulation, 3- low pressure generator for double effect circulation, 4-condensor, 5-absorber, 6- evaporator, 7-solution heat exchanger

In this absorption chiller, high pressure generator was designed as submerged generator while the low pressure generators contained two heat transfer manners. When low pressure generator was heated by the high pressure condensation heat, heat was transfer through submerged boiling. When it was heated by the solar power, heat was transfer through falling film boiling to reduce the temperature difference at the cold end. Other components like the absorbers, the condenser and the evaporator were all designed as falling film heat exchanger. Two generators were set in the same vessel to obtain a compact form. The evaporator was set between two absorbers to reduce the cooling leakage from evaporator to the ambient.

The mean design parameters of the chiller were shown in Table 1.

Table 1. Parameters of the hybrid solar/gas fired absorption chiller.

Gas fired cooling power	1280 kW	Solar cooling power	320 kW
Gas fired heating capacity	1066 kW	Heating output temperature	55.8 -60°C
Chilled water temperature	12 -7 °C	Chilled water flow rate	220 t/h
Chilled water pressure drop	90 Pa	Cooling water temperature	32-37 °C
Cooling water flow rate	343 t/h	Cooling water pressure drop	69 Pa
Hot water temperature	90 -84 °C	Hot water flow rate	61 t/h
Hot water pressure drop	70 Pa	Power of refrigerant pump	0.75 kW
Power of low pressure generating pump	0.75 kW	Power of high pressure generating pump	3.7 kW

3. A real test of the hybrid solar/gas fired absorption system for a commercial building

A system was built based on the hybrid solar/gas fired absorption and tested in a commercial 5 star hotel. System composition and testing environment were shown below.

3.1. System configuration

The system discussed in this paper was a hotel power system. The target of the system was offering cooling in summer and heating in winter. The system also offered hotel hot water supply. The customer would like to utilize solar power to reduce the gas consumption, thus cutting down the operating costs. Figure.2 shows the system configuration of the referred system. Heat sources of the system included the solar collectors (1) (2) (3), auxiliary heat source (8) and the gas fired generator in the chiller (11). They are on the left part of the figure. Except for the heat sources, the system also included water tanks (5) (7), LiBr-water absorption system (11), cooling tower (13), fan coil (12), piping system, pump (4) and control system. Solar collectors offered hotel hot water and absorption chiller used hot water. Auxiliary heat source ensured the hotel hot water has temperature high enough. Gas burner offered heat for double effect absorption refrigeration in summer and heating in winter.

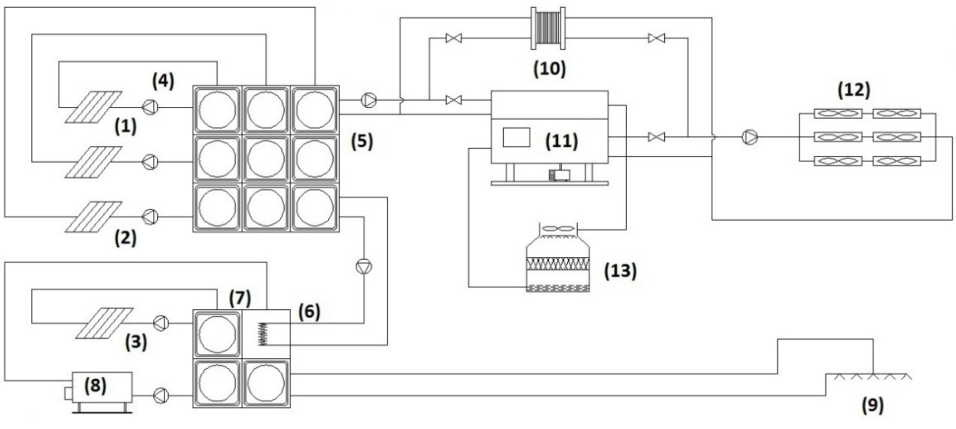


Fig. 2. System configuration of the system for a hotel: Schematics of the hybrid energy system.

(1) Evacuated tube gravity heat pipe solar collector, (2) Evacuated tube horizontal heat pipe solar collector, (3) Evacuated glass tube solar collector, (4) Pump, (5)Water tank for air conditioning, (6) Cooper pipe heat exchanger, (7) Hotel hot water tank, (8) Auxiliary boiler, (9) Hot water use, (10) Plate heat exchanger, (11) Absorption chiller, (12) Fan coil, (13) Cooling tower

3.2. Solar collecting system

Fig. 3. Solar collectors in the system

There were 4 groups of solar collectors as shown in Figure 2 and Figure 3. The 3 major groups of solar collectors included horizontal heat pipe evacuated tube solar collectors (1) and gravity assisted heat pipe evacuated tube solar collectors (2). There were 4950 pipes and 1425 pipes for two types respectively. The whole area for the 3 major groups of solar collectors was 1020 m^2. These 3 groups of solar collectors offered hot water for the absorption chiller, heating or hot water loop. The solar collectors reached a 65% heat collecting efficiency for heating supply or hot water supply while the efficiency was 40~45% when supplying hot water for chiller. Besides, there was a group of heat pipe type evacuated glass tube collectors (3) which only offered hotel hot water. This group had 750 tubes and an area about 120 m^2.

To ensure the system offered hotel water hot enough, there was an auxiliary heat source (8) connected with the hotel hot water tank. The auxiliary heat source was a VB60 type vacuum water boiler utilizing gas as fuel. The boiler had a rated power of 698 kW.

3.3. Real operation procedure

The system was adopted in a 5 star hotel located in Changle, Shandong in China. Chanle is located at 36.69°N and 118.83°E. The absorption chiller, solar collectors and vacuum water boiler were manufactured and installed by the local company. The hotel had two buildings. The larger building had an overall floorage of 14332 m^2 and it was 10000 m^2 for the smaller building. The heating and cooling of the smaller building was fulfilled by the system described in this paper. The larger building adopted a conventional gas fired double effect absorption chiller. The operating parameters of the hybrid solar/gas fired absorption system were tested for a whole year from October 2012 to September 2013. The gas consumptions of the two systems were also recorded for comparison.

4. Results and discussion

In the year round operational process, parameters of the air-conditioning including the solar collector temperature, water tank temperature, high pressure generator temperature, low pressure generator temperature, air conditioning water temperature and the gas consumption were recorded every an hour or a half. Most of the daily operation included alternations between different working modes. The alternations made it inconvenient to identify the property of one specific working mode, so several typical operating conditions with fewer alternations were chosen and discussed first. Common operating conditions were also discussed to show the real operation.

4.1. Solar heating

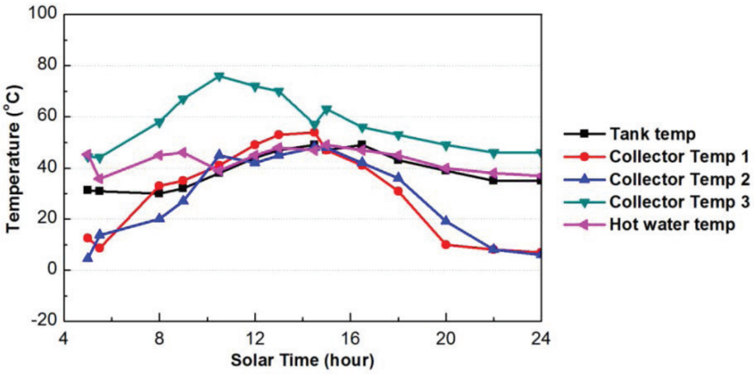


Fig. 4. Daily parameters variations of solar heating mode

Figure 4 shows the parameters changes on Mar 29th 2013. The weather was cloudy and the temperature ranged from 14 °C to -1 °C. The system worked in a solar heating mode for the whole day. When the temperatures of solar collectors were higher than the water tank, the circulation pump between solar collectors and water tank started to pump hot water into the tank and vice versa. In this paper, the "tank temp" refers the temperature of the air-conditioning tank; "hot water temp" refers the temperature of hot water for heating supply; the "collector temp 1" refers the temperature of the first group of solar collectors and the like.

As is shown in the figure, the temperature of water tank was lower than that of the hot water before 11:00. This was because the heating water was supplied to the fan coil from 11:00. The temperature of water tank and hot water were similar after 11:00. The third group of solar collectors was composed of gravity heat pipe collectors that were different from the other two groups. It had a higher temperature. The pump between the third group of solar collectors and the water tank was open all day long while the other two pumps opened in the period of 9:00-14:30 and 10:30-12:00 separately.

The solar collectors were able to fulfill the heating demand in this condition because solar collectors provided water hot enough and heating load was not large.

4.2. Gas fired heating

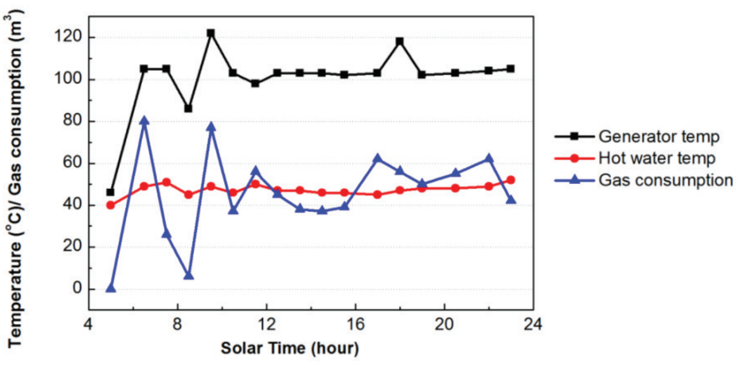


Fig. 5. Daily parameters variations of gas fired heating mode

Figure 5 shows the parameters changes on Dec 20th 2012. The weather was cloudy and the temperature ranged from 3 ^{o}C to -6 ^{o}C. The heating water was offered by the gas fired absorption chiller for the whole day.

The temperature of hot water was similar to that of the solar heating mode. It varied in a small range from 40 ^{o}C to 50 ^{o}C. Gas consumption had the same variation trend with generator temperature. The gas consumption was very small from 7:00 to 8:00 for the heating load during this period was small. It was the opposite reason for the sudden rise of gas consumption at 10:00, 15:30 and 23:00. Except for these variations, the generator temperature and gas consumption were stable. The average hourly gas consumption was 42.7 m3 for the whole day while it is 47.1 m3 for the stable working period from 11:30 to 23:00.

4.3. Common heating condition

Most heating conditions contained the alternate operation of solar heating and gas fired heating. Figure 6 shows the parameters changes of a common heating condition. It was on Dec 19th 2012, sunny day with ambient temperature varied from 2 ^{o}C to -8 ^{o}C.

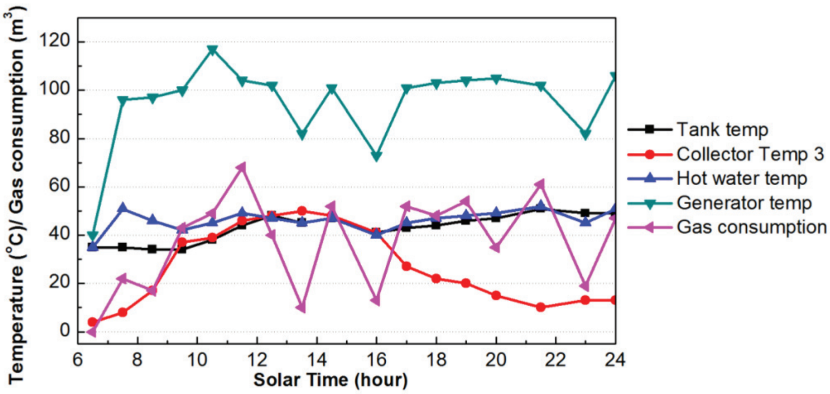


Fig. 6. Daily parameters variations of common heating condition

As is shown in the figure, the gas consumption varied with the generator temperature. There were 3 sudden fallings of generator temperature and gas consumption. The sudden fallings were caused by the turning-off of the gas fired absorption chiller. During the period of 12:30-13:30 and 14:30-17:00, the water tank temperature was raised high enough to supply heating by the solar collectors. Then the gas fired heating was turned off. The other turning-off of gas fired heating was caused by the decline of heating demand.

Except for the two turning-offs of the gas burner during the daytime, the hot water temperature varied with the generator temperature. The average gas consumption per hour except for the 3.5 hours solar heating was 45 m3. This was similar to the results of the last part. The average gas consumption for the whole day was 36 m3 which had 20% energy saving ratio comparing with the pure gas fired working mode.

4.4. Solar cooling

Figure 7 shows the parameters variations on June 15th 2013. The weather was sunny and temperature ranged from 30 ^{o}C to 16 ^{o}C. The system worked in a solar cooling mode during the period of 10:00-14:00 and 17:00-21:30. In the spare time, the air conditioning pump was turned off. As is shown in the figure, the water tank temperature varied with the temperature of the 3 groups of solar collectors in a range of 56 ^{o}C -85.8 ^{o}C during the day time. The collector temperatures decreased faster than the water tank temperature after the sunset. The cooling water temperature stayed stable about 30 ^{o}C while the chilled water temperature varied from 10 ^{o}C -18 ^{o}C. Considering the solar collector had a 40~45% efficiency when supplying hot water for chiller and the absorption chiller had a COP about 0.75, the solar cooling COP was about 0.28-0.34.

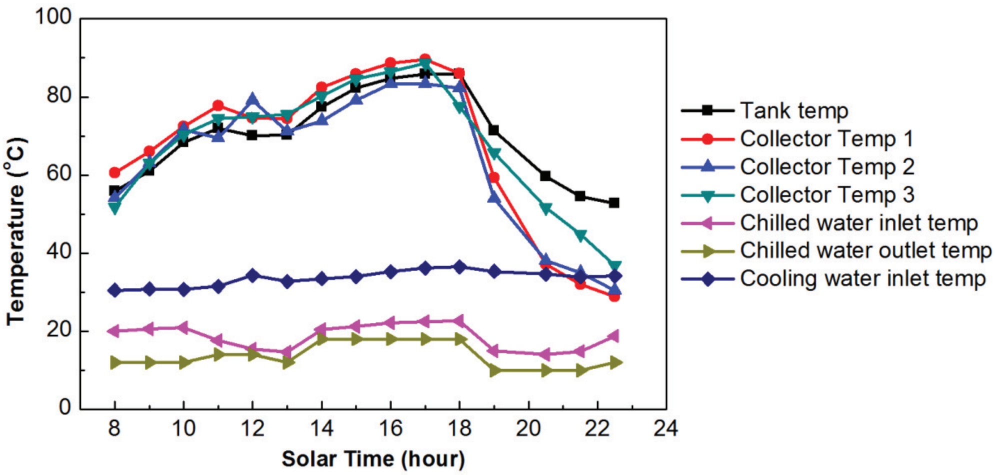


Fig. 7. Daily parameters variations of solar cooling mode

Among the 3 groups of solar collectors, the third group still obtained the highest temperature just the same as the results on March 29th 2013. After 13:00, temperature of the second group of collectors was lower than the water tank temperature that the pump between the collector and the water tank was closed. After the sunset at about18:00, solar collector temperature decreased fast due to the reduced solar radiation. The solar collector pumps were turned off at this time.

Before the air conditioning pump started to work at 10:00, the water tank temperature kept rising. After the pump started to work, the water tank temperature stopped rising due to the consumption of the absorption chiller. The water tank temperature decreased fast after 18:00 since the absorption chiller consumed the hot water while the solar collector could not offers hot water to the tank. Besides, the decrease of chilled water temperature at 10:00 and 18:00 was reasonable considering the alternate operation of the air conditioning pump and its influence.

4.5. Common cooling condition

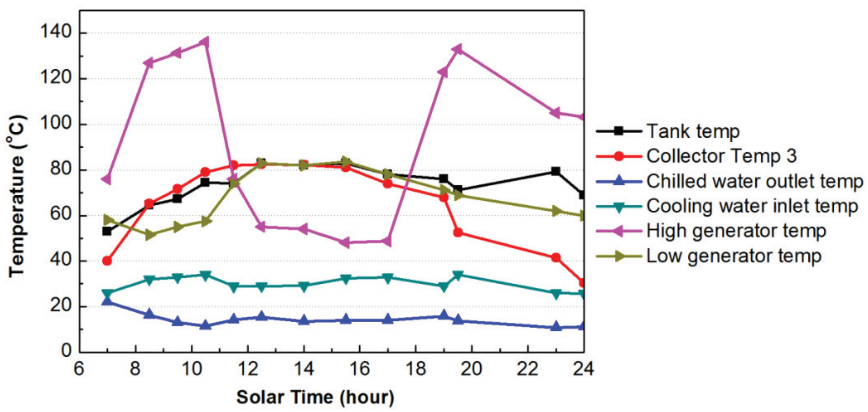


Fig. 8. Daily parameters variations of common cooling condition

As discussed in the last part, the cooling was offered by the solar driven absorption chiller for the whole day. This was the consequence of well coupling between solar power and cooling demand. This was rare because the well coupling only existed in the season change period. In the most time of the summer, cooling demand was high during the whole day while the solar power could afford the absorption chiller only in a small period. On the other hand, the condition that the absorption chiller worked in gas fired cooling mode for the whole day doesn't exist during the whole year testing process. There would always be a period that the system worked in solar cooling mode.

The parameters changes of a common condition were shown in Figure 8. It was August 19th 2013. The weather was sunny while the ambient temperature varied from 32 ^{o}C to 22 ^{o}C. As is shown in Figure 8, the most staring part in the figure was the sudden change of the high generator temperature at 11:30 and 19:00. This was the results of the alternation between gas fired cooling mode and the solar cooling mode. When the absorption chiller worked in the gas fired cooling mode, the temperature of the high pressure generator was about 130 ^{o}C. When the absorption chiller worked in the solar cooling mode, the temperature of generator was about 80 ^{o}C. The cooling water temperature varied from 25.7^{o}C -34 ^{o}C. The chilled water temperature varied from 16.3 ^{o}C to 10.8 ^{o}C except for the 22 ^{o}C at 7:00.

Before 11:30, the temperature of the water tank was lower than 75 ^{o}C which was not able to offer enough cooling output. The system worked in gas fired cooling mode and was assisted by the solar cooling. From 11:30 to the sunset, the water was hot enough to activate the absorption chiller. In this period, the water tank temperature, the solar collector temperature and the generator temperature were almost the same. Besides, the water tank temperature stayed stable while offering heat to the absorption chiller. This means the solar collectors had enough power output to fulfill the cooling demand. After the sunset at about 18:30, the collector temperature decreased fast, the water tank temperature would fall fast if the absorption chiller was still activated by the water from the tank. So the system alternated to the gas fired cooling mode again.

The gas consumptions of the first period of gas fired mode were 118 m3 in total and 26.2 m3 per hour. They were 139 m3 in total and 27.8 m3 per hour for the second period. The average gas consumptions were similar. If the gas consumption was averaged for the whole day, it was 15.1 m3 per hour. This meant the utilization of solar energy saved 44% of the gas consumption. What should be noted was that this energy saving ratio depends on the weather and the operating time span of the solar cooling mode.

The COP of gas fired double effect absorption refrigeration was about 1.1-1.3. The solar cooling offered 44% of the cooling demand. So, the daily average COP calculating from the entire cooling production and the gas firing heat was about 1.96 -2.32. If the solar power was counted as the heat input, the average COP was about 0.95 -1.06.

4.6. Energy consumption comparison

In the above analysis, several conditions were discussed and energy saving ratios were calculated. These ratios were just for one day that it was different to another. To show the energy saving effects of the discussed system, the gas consumptions of the hybrid energy system and the conventional gas fired absorption energy system in another building of the hotel were compared. The two buildings were located in the same yard that the weather, solar radiation and checking-in ratio were almost the same. There was only difference in floorage. To give a fair comparison, the gas consumption of the conventional system was multiplied by the area ratio. Figure 9 shows the monthly consumption comparison.

The overall tendencies of two systems were similar. Heating in winter consumed the largest amount of gas. Cooling in summer had the second gas consumption. The gas consumption was the small during transition seasons.

As is shown in the figure, gas consumptions of the two systems were similar during transition season. This proves the fairness of the comparison. On the other hand, it was obvious that the conventional system consumed more gas during the period of December- February and June- August. Especially in December and August, the gas consumptions of the conventional system were more than the twice of consumptions of the hybrid energy system. For the whole year, the conventional system consumed 356080 m3 gases while the hybrid energy system consumed 125000 m3 gases. Calculating in unit area, the yearly gas consumption of the hybrid energy system was 50.3% of the conventional system consumption. The hybrid solar/gas fired absorption system was proved energy saving.

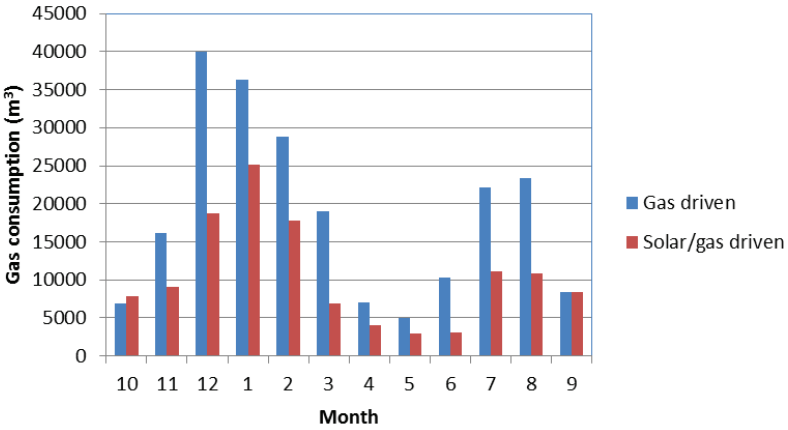


Fig. 9. Gas consumption of the hybrid energy system and the conventional system

5. Conclusions

In this paper, a system composed of 4 groups of solar collectors, a hybrid solar/gas fired absorption chiller, two water tanks, an auxiliary vacuum boiler and the fan coil was introduced. The hybrid energy system offered heating, cooling and hotel water through solar power at first and gas firing as a backup. One year operation of the hybrid energy system in a commercial 5 star hotel was recorded. Three typical conditions including solar heating, gas fired heating, solar cooling and two common conditions were discussed in detail. The temperature variations were analyzed. Gas consumption and energy saving ratio of whole year were calculated. Several conclusions are made below:

(1).Real operations of the heating and cooling supply are complex processes which can hardly be afforded by simply solar energy.

(2).The hybrid solar-gas fired absorption system is able to supply all the heating, cooling and hotel hot water needs for a building. The operation is stable and reliable.

(3).Solar energy is able to reduce the energy consumption of a conventional gas fired absorption system in a large extent. The gas consumption of the hybrid energy system has a 49.7% energy saving ratio compared with the conventional gas fired system.

Acknowledgements

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